PRE-LAUNCH ABSOLUTE RADIOMETRIC CALIBRATION OF LANDSAT-4 PROTOFLIGHT THEMATIC MAPPER

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The Thematic Mapper (TM) sensor is a scanning radiometer for use in land remote sensing on Landsat-4 and Landsat-5. From both scientific and applications perspectives, the usefulness of TM digital imagery is significantly determined by its radiometric characteristics. This includes both the accuracy to which the dynamic range is known and its radiometric reproducibility or precision. This paper summarizes and analyzes results from several pre-launch tests with a 122-cm Integrating Sphere (IS) used as part of the absolute radiometric calibration experiments for the "protoflight" TM sensor carried on the Landsat-4 satellite.

TM RADIOMETRIC CALIBRATION

A radiometric calibration curve for each of the ninety-six reflective channels (detectors) on TM was calculated from a least squares fit of raw radiance, $\bar{\bar{L}}_R$, in digital numbers (DN) versus known spectral radiance, L_λ, of the external IS in units of $mWcm^{-2}ster^{-1}um^{-1}$:

$$= \bar{\bar{L}}_R = O_{IS} + G_{IS} * L_{\lambda,IS} \qquad (1)$$

where O_{IS} is the offset and G_{IS} is the gain for a specific channel, and $\bar{\bar{L}}_R$ is usually averaged over 25 mid-scan values and 100 scans. For example,

on 19 March 1982, such an experiment was run under ambient conditions of temperature and pressure and gave the following results for channel 9 of band 3:

$$= \bar{\bar{L}}_R = (1.53 \pm 0.43) + (10.55 \pm .04)\ L_{\lambda,IS} \qquad (2)$$

where the twenty-one IS spectral radiance levels were those determined in a subsequent recalibration in May 1982. One measure of the linearity of this regression is the ±0.4% coefficient of variation of the gain. This is typical of the linear response to radiance for all channels on TM. Both the gain and the offset of these solid state detectors are more stable with time than the previous generation of photomultiplier tubes used in three bands on the MSS sensor. Because of this stability, fixed electronic components on TM could be selected, in order to obtain nearly identical gains and offsets for all sixteen channels in the band.

The success of this effort is illustrated in Table 1, which summarizes information on gains and offsets for Landsat-4 TM.

Offsets are held at a fixed level by a dark current (DC) restoration circuit which is activated at the end of each scan on TM. Unlike MSS, the offset on TM was set about two counts above zero to increase the ability to measure background noise. Offset values differ by less than a count from the measured background values of radiance where there is no external source. This low uncertainty in the offset is another indication of the degree of linearity of observed raw sensor radiance in DN (0-255) versus known radiance, albeit less significant than the ±0.4% uncertainty in the gain.

A major objective of radiometric calibration in the ground processing of digital imagery from scanners has been to minimize the striping associated with unequal responsivities of the different channels in a specific band. If one could assure that the gains remained constant with time, the standard deviations of the offset and the coefficients of variation of the gains in Table 1 provide a quantitative measure of the degree of striping that could be expected without calibration. The ninety-six individual gains and offsets themselves provide the basis for destriping the image. Since the maximum range of within-band variation is from 3 to 7%, TM imagery may be usable for

TABLE 1

PRE-LAUNCH ABSOLUTE RADIOMETRIC GAIN AND OFFSET BY CHANNEL OF REFLECTIVE BANDS ON LANDSAT-4 PROTOFLIGHT THEMATIC MAPPER SENSOR (TM/PF) FROM LEAST SQUARES OF FIT OF RAW RADIANCE L_R, IN DIGITIAL NUMBER (DN) VERSUS KNOWN SPECTRAL RADIANCE L_λ, OF EXTERNAL 122cm INTEGRATING SPHERE (IS):

$$\bar{\bar{L}}_R = 0_{IS} + G_{IS} {}^{*} L_{\lambda,IS}$$

(FROM AMBIENT TEST OF TM WITH IS AT 12 EST ON 19 MARCH 1982 AT GE IN VALLEY FORGE, PA USING SPHERE RECALIBRATION OF MAY 1982 AT SBRC IN SANTA BARBARA, CA)

TM BAND NUMBER	BAND-AVERAGE OFFSET FOR 16 INDIVIDUAL CHANNELS		BAND-AVERAGE GAIN FOR 16 INDIVIDUAL CHANNELS	
	MEAN OFFSET O (DN)	STANDARD DEVIATION σ_O (DN)	MEAN GAIN G (DN PER $mWcm^{-2}ster^{-1}\mu m^{-1}$)	COEFFICIENT OF VARIATION $100\sigma_G/G$ (%)
1	2.58	±0.18	15.78	±0.54
2	2.44	±0.16	8.10	±0.89
3	1.58	±0.20	10.62	±0.76
4	1.91	±0.22	10.90	±1.23
5	3.02	±0.11	77.24	±0.53
7	2.41	±0.20	147.12	±0.72

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some purposes, without radiometric calibration. However, scientific applications such as comparison of radiances from sensors on different satellites, or separate independent information by combination of spectral bands require that radiometric calibration be applied to at least the level of reproducibility of the measurements. Radiometric calibration is also desirable for digital applications such as classification or for creation of stretched enhancements, since individual DN levels are discernible in both cases. Individual values of gain and offset for each reflective channel are given in this paper.

TM RADIOMETRIC SENSITIVITY

Radiometric resolution on TM is greater than that of the Multispectral Scanner (MSS) sensor. Specifications for TM called for minimum signal-to-noise ratios (SNR), as indicated in column 2 of Table 2 (Engle, 1980). While the rms radiometric precision can be no greater than the $\pm 1/\sqrt{12}$ quantization error associated with the 8-bit multiplexer on TM, the measured SNRs were much greater than specified, as summarized in Table 2, especially for the three bands on the cooled focal plane, namely two short-wave infrared (SWIR) bands and one thermal infrared (TIR) band. All channels perform normally with only three exceptions: 1) channel 3 in band 5 is dead, 2) channel 2 in Band 2 is sufficiently noisy to not meet specifications and, 3) channel 4 in Band 2 has a slow electronic response, which resulted in a degraded spatial resolution for boundaries. These three channels were excluded from the SNR averages in Table 2. Band 6 data is only approximate. Individual values for SNR were interpolated at the $\bar{\bar{L}}_R$ = 243DN from linear fits of up to 21 measurements of SNR and IS radiance L_λ. Included within the empirical observations of noise are uncertainties associated with unequal bins (intervals) in the analog-to-digital converter on TM, which also contribute to the scatter of the linear fit of SNR versus L_λ. As seen in Table 2, observed rms radiometric precision on TM at full scale is between 3 and 10 parts per thousand, or approximately one digital number for the 256 DN levels, or bins.

TABLE 2

LANDSAT-4 PROTOFLIGHT THEMATIC MAPPER (TM/PF) POST-LAUNCH RADIOMETRIC BAND CALIBRATION CONSTANTS
(FOR SCROUNGE-ERA PROCESSING PRIOR TO AUGUST, 1983)

TM BAND NUMBER	DYNAMIC RANGE AFTER GROUND PROCESSING		SPECTRAL RADIANCE TO DIGITAL NUMBER $L_R = 0°(B) + G°(B) \cdot L_\lambda$		DIGITAL NUMBER TO SPECTRAL RADIANCE $L_\lambda = \beta + \gamma \cdot L_R$	
	RMIN AT $L_{R_{cal}}$ = 0 DN $\frac{mW}{cm^2\ ster\ \mu m}$	RMAX AT $L_{R_{cal}}$ = 255 DN $\frac{mW}{cm^2\ ster\ \mu m}$	OFFSET 0° (B) DN	GAIN G°(B) $\frac{DN}{mW\ cm^{-2}\ ster^{-1}\ \mu m^{-1}}$	INTERCEPT β $\frac{mW}{cm^2\ ster\ \mu m}$	SLOPE γ $\frac{mW}{cm^2\ ster\ \mu m\ DN}$
1	−0.152	15.842	2.423	15.943	−0.152	0.06272
2	−0.284	30.817	2.328	8.199	−0.284	0.12197
3	−0.117	23.463	1.265	10.814	−0.117	0.09247
4	−0.151	22.432	1.555	11.298	−0.151	0.08856
5	−0.037	3.242	2.877	77.768	−0.037	0.01286
7	−0.015	1.700	2.230	148.688	−0.015	0.006725
6(CH 4)	0.20	1.564	−37.2	186.0	0.20	0.00535

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The on-board Internal Calibrator (IC) in the TM sensor is designed to monitor gain and offset of the channels as a function of time (Engel, 1980). There are three IC lamps for the reflective bands which are normally operated in an automatic sequence of eight light levels. These data are collected by intercepting the optical axis of the telescope with a shutter at the end of each scan. Each light level is maintained for about 40 scans in this automatic sequence mode. Following the calibration of each channel by the IS, the automatic sequencer was run to measure the average DN value of the pulses for each level and to calculate an effective spectral radiance for each of these eight IC lamp configurations for all reflective channels. Using Channel 9 of Band 3 as an illustration, the previous IS calibration curve represented by Equation 2 was inverted:

$$L_{\lambda}^{\circ}(\ell, C) = 0.144 + 0.09394\, \bar{P}^{\circ}(\ell, C) \qquad (3)$$

where $\bar{P}^{\circ}(\ell, C)$ is the observed average pulse value on the date of IC calibration in DN for a particular IC lamp configuration ℓ, and $L_{\lambda}^{\circ}(\ell, C)$ is its effective spectral radiance in $mWcm^{-2}ster^{-1}um^{-1}$. Several transfer tests of this type were run and compared. The final values chosen for post-launch radiometric correction were from a run on March 20, 1982 and are tabulated in this paper.

No correction was attempted in these tables for the "vacuum shift" difference between IC pulse values taken under ambient conditions and pre-launch thermal vacuum (TV) tests. Results of some TV tests are also summarized in this paper. Each time an image is taken in orbit, IC pulses are collected and regressed against these effective spectral radiances to obtain a new value of apparent gain, G(C), and offset, O(C), for each channel:

$$P(\ell,C) - O(C) + G(C) * L_{\lambda}^{\circ}(\ell,C) \qquad (4)$$

under the assumption of constant lamp radiance.

Results from the monitoring of apparent changes in gain after launch from IC data are summarized in a companion paper for the three visible (VIS) and near infrared (NIR) bands on the primary focal plane (PFP) and for the two short wave infrared bands (SWIR) on the cooled focal plane (CFP) (Barker, 1984). Such changes in gain over the first year and a half of operation have covered a range of less than 10% for all six reflective bands and are of minimal consequence to users, as long as the radiometric correction performed during "preprocessing" of digital tapes is applied correctly.

For the thermal infrared (TIR) band, a two-point calibration is used to follow changes in gain with time. One point is the temperature of the shutter which is inserted into the optical axis at the end of each scan. This is also the reference for DC restoration on Band 6. The other point is radiance from an internal black body which is reflected to the cooled focal plane (CFP) by a mirror on the shutter. A 30% reduction in the gains for the four TIR channels was observed during the first six months of operation. Gain was restored to pre-launch values by out-gassing, i.e., turning on the TM heaters around the CFP, in January 1983. Results on thermal calibration are reported elsewhere (Lansing and Barker, 1984 and Lansing, 1983).

TM DYNAMIC RANGE AFTER CALIBRATION

One goal of radiometric calibration is to express all calibrated radiance within one band in a common radiance range. The range is called the post-calibration dynamic range of a band and is defined by the values at its two limits, RMIN and RMAX. RMIN is the spectral radiance, L_λ, corresponding to a calibrated radiance, L_{cal}, at a DN value of zero. Similarly, RMAX for an 8-bit sensor is the radiance at $L_{cal} = 255$ DN. To convert to in-band radiance, one simply multiplies the spectral radiance by the bandwidth of that band. Spectral response curves for TM bands on Landsat-4 and -5 can be used to compute precise bandwidths and are given elsewhere (Markham and Barker, 1984).

Two equivalent methods of expressing dynamic range can be given in terms of RMIN and RMAX. One is the band offset $O°(B)$ and gain $G°(B)$ of L_{cal} versus L_λ. The other is its linear inverse, namely L_λ versus L_{cal}, which

can be quantified by an intercept (β) and a slope (γ) in order to distinquish them from offset and gain. Offset and gain are defined in terms of RMIN and RMAX by two equations:

$$L_{cal} = \left(\frac{\text{Range} * \text{RMIN}}{\text{RMAX} - \text{RMIN}}\right) + \left(\frac{\text{Range}}{\text{RMAX} - \text{RMIN}}\right) L_\lambda \tag{5}$$

or $$L_{cal} = O°(B) + G°(B) * L_\lambda \tag{6}$$

where the range is 255 for TM and the symbols O°(B) and G°(B) are used to provide an explicit difference between the common and constant offset O°(B) and gain G°(B) for all channels after calibration and the variable pre-calibration offset O(C) and gain G(C) derived from the regression fit of Equation 4. For the numbers in Table 3, O°(B) is in units of DN and G°(B) in DN per $mWcm^{-2}ster^{-1}um^{-1}$.

In the same way, intercept and slope are defined by:

$$L_\lambda = \text{RMIN} + \left(\frac{\text{RMAX} - \text{RMIN}}{\text{Range}}\right) L_{cal} \tag{7}$$

or $$L_\lambda = \beta + \gamma * L_{cal} \tag{8}$$

where Equation 8 is one form used for converting DN values into spectral or in-band radiance. For the TM band calibration constants in Table 3, β is in spectral radiance units of $mWcm^{-2}ster^{-1}um^{-1}$ per DN. Numbers in Table 3 were calculated from RMIN and RMAX. Different values may have been inadvertantly introduced in the digitally processed tapes distributed to users due to rounding and different choices of bandwidths for calculating in-band radiance. In addition, RMIN values were set to zero and RMAX values to original specifications at the start of processing by TIPS (TM Image Processing System) in August, 1983. This change will be followed by at least two more changes in RMIN and RMAX values during the 1984 TM research period (Barker, 1984). The reason for this is primarily to use observed pre-launch and in-orbit data on Landsat-5 to find a common post-calibration dynamic range for both Landsat-4 and Landsat-5. In addition, recalibration of the absolute

TABLE 3

LANDSAT-4 PROTOFLIGHT THEMATIC MAPPER (TM/PF) POST-LAUNCH RADIOMETRIC BAND CALIBRATION CONSTANTS (FOR SCROUNGE-ERA PROCESSING PRIOR TO AUGUST, 1983)

TM BAND NUMBER	DYNAMIC RANGE AFTER GROUND PROCESSING		SPECTRAL RADIANCE TO DIGITAL NUMBER $L_R = KO + KG \cdot L_\lambda$		DIGITAL NUMBER TO SPECTRAL RADIANCE $L_\lambda = \beta + \gamma \cdot L_R$	
	RMIN AT $L_R = 0$ DN $\left(\frac{mW}{cm^2\ ster\ \mu m}\right)$	RMAX AT $L_R = 255$ DN $\left(\frac{mW}{cm^2\ ster\ \mu m}\right)$	OFFSET KO (DN)	GAIN KG $\left(\frac{DN}{mW\ cm^{-2}\ ster^{-1}\ \mu m^{-1}}\right)$	INTERCEPT β $\left(\frac{mW}{cm^2\ ster\ \mu m}\right)$	SLOPE γ $\left(\frac{mW}{cm^2\ ster\ \mu m\ DN}\right)$
1	−0.152	15.842	2.423	15.943	−0.152	0.06272
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7	−0.015	1.700	2.230	148.688	−0.015	0.006725
6(CH 4)	0.20	1.564	−37.2	186.0	0.20	0.00535

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radiance values of the integrating sphere is planned as well as possible insertion of temperature-dependent algorithms. Users should therefore refer to values of calibration constants in the ancillary digital data on the tapes to verify the numbers that were actually used in the radiometric processing of the images in each set of tapes.

Errors associated with absolute calibration are discussed. Specifications call for an absolute calibration accuracy within 10% at full scale. An rms averaging of estimated precision in each transfer step from an NBS standard lamp to the IC lamps suggests a rms error of about 6%. Post-launch calibration with ground targets at White Sands, New Mexico are still being evaluated (Slater et all., 1984). Ten tests performed to transfer the channel absolute calibration in the internal calibrator showed a 5% range at full scale, except for Band 5 which showed differences up to 10%. Errors quoted above are associated with random reproducibilty and do not include possible systematic errors such as: 1) calibration of NBS lamps, 2) distance dependence of calibration of integrating sphere, 3) temperature dependence of pulses from the internal calibrator (of the order of 5% over 10°C range for some channels), 4) vacuum shift, 5) differences in conditions at times of pre-launch tests and in-orbit observations, 6) random scan correlated shifts, 7) within-scan electronic droop, and 8) within-line bright-target saturation.

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